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INSTRUMENTATION FOR MEASURING IN-VITRO 3-D RELATIVE MOTION OF INTERVERTEBRAL JOINTS

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ABSTRACT

The paper presents the state of the art in measuring in-vitro 3-D relative motion of synovial joints and identifies the need for developing better instrumentation for studying the motion characteristics of intervertebral joints. The paper examines the sensitivity of the linkage transducer in measuring the data needed for motion analysis of cadaver knees. Based on this analysis, the paper proposes two modifications in the linkage transducer to collect three dimensional relative motion data for studying the kineto, elasto, static and dynamic response of the intervertebral joints subjected to a variety of conditions.

INTRODUCTION

In studying the static and dynamic force response of a human spine, kinematics and elastic properties of the intervertebral joint play a significant role. It is well accepted that the intervertebral joint executes three dimensional motion and that it has interrelated six components of motion. While there exists a number of static and dynamic force response simulation models, and while the need for incorporating the kinematics of the intervertebral joint is fully realized, a systematic approach in incorporating such kinematic influence of the intervertebral joint in the simulation model has not been fully developed. The failure to incorporate this kinematic influence is due to the lack of fully developed and tested experimental methods in obtaining 3-D motion data of the intervertebral joint. This report presents a brief survey of the available measurement techniques to collect motion data for intervertebral joints and examines very closely the linkage transducer in collecting such data.

SURVEY OF THE MEASUREMENT TECHNIQUES

The data describing the relative motion of intervertebral joints are collected by designing a suitable in-vivo or in-vitro laboratory experiment. An in-vivo data collection involves use of buble goniometer [1], shadow technique, and the roentgenograph technique for recording discrete positions of the spine or the cineroentgenograph technique for recording continuous motion. An in vitro experimental procedure for data collection appears to have more freedom to record detailed descriptions of the relative motion of vertebrae. Planar motion data on the intervertebral joint motion were obtained [2, 3] using single roentgenograph measurement. Simultaneous data from two x-rays taken in intersecting planes were used [4, 5, 6] to measure the spatial motion of vertebrae. Externally applied electronic transducer systems were used [7, 8] to measure axial rotation of vertebral bodies. An electromechanical motion transducer system was developed [9] to measure the motion of lumbar spine using mercury filled tubes as strain elements. Motion transducer systems to measure spatial relative motion have been also used in studies of other anatomical joints. For example, a multiloop instrument system was used [10] to measure jaw motion. An instrumented linkage [11] was developed to study mandibular motion. Single and multiloop linkage instrumented measurement techniques were developed [12, 13, 14] to measure the spatial motion of the canine shoulder and of the human knee joint [15]. Cineradiography was used to measure the motion at the wrist [16]. Table 1 presents an analysis of the instrumentation techniques for collecting the in-vitro data on the relative motion of synovial joints. The various techniques are compared for their suitability for three-dimensional data collection under static and dynamic mode, accuracy, simplicity and economy. This analysis reveals that the instrumented linkage transducers offer the most accurate and economical means of measuring general space motion at intervertebral joints.

TABLE 1

Comparison of Available Instrumentation Techniques to Measure In-vitro Relative Motion of Synovial Joints

Instrumentation Technique	Components of Motion	Accuracy	Cost	Dynamic Motion Measurement	Remarks
Buble Goniometer [1]	Intersegmental angular measurement, planar, not suitable for 3-D motion component measurement.	Inaccuracy in the method of measurement since the line of reference shifts giving wrong values of flexion, extension.		Not suitable.	
Cineradiography [16]	Qualitative description of the planar motion.	Poor resolution and accuracy in identifying the body points on film.		Can be used for measurement of planar motion.	
Bi-planar x-rays [4,5,6]	Measures all six components of 3-D space motion.	Graphical in accuracies and distortion errors.	Not economical for measurement of continuous motion where large number of x-rays are needed.	Not suitable.	Needs an elaborate set-up.
Externally applied electronic transducer [7,8]	Total angular rotation only in horizontal plane measured at each pin level-single component of motion measurement.	1. Accuracy to 1 degree. 2. Interference with normal mode of motion. 3. Steinmann pins can become loose during		Dynamic loads can loosen the Steinmann pins causing inaccuracies in the measurement of axial rotation.	Pelvic fixation devices necessary.

TABLE 1 continued

Instrumentation Technique	Components of Motion	Accuracy	Cost	Dynamic Motion Measurement	Remarks
		lateral bending. 4. Individual effort involved makes the measurement subjective.			
Electromechanical Motion Transducer [9]	Measures all six components of motion.	1. Reported errors due to long term drift of transducer circuitary. 2. Most susceptible to errors in measurement of axial rotation and A-P displacement.		Not suitable due to inertia of the fluid columns.	Uses large liquid mercury filled tubes as strain elements.
Linkage Transducers [10-16]	Measures all six components of motion.	1. Repetative results can be obtained. 2. Accurate to the resolution of rotary potentiometers. 3. Rigid mounting can be achieved with ease. 4. Light weight and no interference with the normal mode of motion. 5. Continuous data can be obtained on the relative motion.	Less expensive than the x-ray measurements.	Most suitable for dynamic motion measurement. The link-deflections due to dynamic loads are order of magnitude less than the resulting intervertebral displacements.	Needs a multi-channel voltmeter for static measurements and a voltage recorder for dynamic measurement.

KINEMATIC CRITERIA OF THE LINKAGE TRANSDUCERS

A linkage transducer has six kink-links, and six kinematic links connected by six pin joints. When the transducer is connected to a human joint to measure its relative motion, it becomes a closed-loop kinematic linkage integrating within it the human joint as a kinematic pair, instantaneously having one degree of freedom. Since the relative motion of a human joint, (regardless of the manner in which it executes relative motion) can always be described by an instantaneous screw motion, at each instant, the six link transducer adds a screw part of one degree of freedom to its configuration. Thus, the total degrees of freedom of the kinematic pairs of the linkage system, including the human joint, is seven. According to Artobolevski and Dobrovaleski's mobility criteria [19]

$$F = 6(N-1) - 5P_1 - 4P_2 - 3P_3 - 2P_4 - P_5$$

(where F = degrees of freedom of the linkage system, N = number of links, P_k = number of kinematic pairs with k degrees of freedom), the system has at each instant constrained motion. That is, the linkage transducer having six pin-joints connected by six links and connected to a human joint will execute constrained relative motion. If the six pin-joints are replaced by six rotary potentiometers, the angular displacement recorded by the potentiometer will provide the necessary data to describe at each instant an equivalent seventh screw pair. If the human joint is in reality a pin-joint, a slider pair, or a helical pair, the equivalent seventh pair is expected to have its respective pitch value zero, infinity or constant. However, in general, the human joints do not represent such simple values and as a consequence, we have the human joint described by a series of instantaneous screws, each time having different location, orientation, and pitch values. Such a series of screws represent the locus of the instantaneous screw axes associated with definite pitch values. This locus is defined as the axode. By examining the inverse of the motion of the rigid body with respect to a fixed frame, it then becomes possible to obtain a conjugate axode. Thus, with the help of an axode and its conjugate axode, it becomes possible to describe theoretically the kinematic performance of any human joint. The data to find the instantaneous screws and the axode, are of course obtained using a linkage transducer.

Since the human joint varies in size, shape and location, it is difficult to arrive at an all purpose linkage transducer to obtain 3-D motion data. The need to arrive at all possible types and kinds of linkage transducers, therefore, becomes a necessity if the human-joint study is required to account for the kinematic influence of the joints.

A transducer can be used either to measure linear displacements or angular displacements. The corresponding kinematic pairs executing linear or angular displacements are respectively, the sliding or the revolute pair. Using the criterion that the sum of the degrees of freedom of the linkage transducer is six and that the human joint will at each instant contribute one helical pair, we find a total of 22 linkage transducers with rotary and linear potentiometers. These are schematically shown in Figures 1 through 22.

The advantage of enumerating all possible linkage transducers is that we are now in a position to select the one of the possible twenty-two linkage transducers on the basis of compactness and availability of rotary and linear potentiometers. The criterion of compactness of a linkage transducer will require one to design for optimum dimensions of the linkage involving its kinematic links, kink-links and orientation of the axes of the transducers. In addition, the linkage transducer is required to have a maximum range of gross motion, so that the joint motion can be studied in its entirety.

OUR EXPERIENCE IN USING THE LINKAGE TRANSDUCER

In testing the motion characteristics of a human knee, one is faced with the similar problem of measuring the 3-D motion data of the knee joint [17]. Just as in the case of the intervertebral joint, the knee joint has all the six interrelated components of motion [12, 13, 14]. Precise measurement of these six components of motion is just as challenging as it is for the intervertebral joints. A linkage transducer with six rotary potentiometer was designed specifically to measure the motion components of the knee joint. All the six potentiometers were servo mounted in the linkage. The readings of these six potentiometers were monitored on a digital voltmeter. The total weight of the linkage transducer with the potentiometers is 15 ozs. Table 2 presents the set of data collected for flexion extension of a cadaver knee. The data were collected using the linkage transducer. These data were collected in repetitive manner to insure the accuracy of the linkage transducer. Our ex-

TABLE 2

SPECIMAN NO: 4

FLEXION - EXTENSION

ANGLE DEG	POT 1	POT 2	POT 3	POT 4	POT 5	POT 6	LOAD LB	REMARKS
0.0	2.14	7.71	6.09	0.00	0.84	1.50	0	—
15	2.26	7.72	6.03	0.01	0.90	1.41	0	—
30	2.48	7.62	5.94	0.02	0.98	1.15	0	—
45	2.58	7.67	5.85	0.01	1.05	0.62	0	—
60	2.59	7.63	5.81	0.10	1.02	0.23	0	—
75	2.60	7.57	5.78	0.21	0.93	0.01	0	—
90	2.86	7.62	5.63	0.28	1.01	9.87	0	—

perience in using the linkage transducer revealed the following:

1. Ease of measuring the six components of motion of the knee joint.
2. Light weight of the transducer.
3. Ease of mounting and removal of the transducer on the knee specimen.
4. Accurate and reliable measurements.

The potentiometers used for this purpose have the specifications presented in Table 3.

TABLE 3

WATERS POTENTIOMETERS BY WATERS MFG. INC.
Wayland, MA 01778

Size	7/8" body diameter
Resistance Range & Tolerance	10 Ω - 250 K ± 5%
Resistance Value	1 K
Ind. Linearity	± 1%
Effective Elec Travel	$320^{o} \pm 5^{o}$
Mechanical Rotation	360^{o}
Starting Torque	< .5 oz-in
Shaft End Play	.005" max
Life	5×10^{5} cycles

SPINAL MOTION AND ITS PRECISE 3-D MEASUREMENT

The human spine can execute motion independently in the Sagittal plane, frontal plane and horizontal plane. These independent motions can be combined in many forms and orders, hence the true study of the three dimensional intervertebral motion must be done without having to decompose the motion into the three anatomical planes. The relative motion of each of the 24 vertebrae has at most six components of motion which are governed by a functional relationship. Such functional relationships or the "pattern of motion" vary with the varying modes of motion executed by the spine subjected to a variety of static or dynamic conditions. Such functional relationships between the components of motion of a vertebra can be quantitatively described by the locus of the instantaneous screw of motion. This locus which is termed as the axode is the true "signature" of the three dimensional intervertebral motion. The axode and its conjugate defines this motion uniquely in terms of its characteristic parameters. In order to perform such kinematic analysis of the intervertebral motion, it is necessary to collect the 3-D motion data in an accurate and continuous mode. As discussed in previous sections, the instrumented linkage transducer, Figure 23, provides the best choice. However, the linkage transducer used for the motion measurement of human knee joint, needs to be redesigned in order to function properly in the space availalbe between two successive vertebrae. Such redesign involves arriving at an optimum set of kinematic parameters of the linkage, small diameter potentiometers and a convenient way of installing the linkage transducer. The criterian for obtaining the optimum design parameters of link lengths, offset distance along the rotary axis of the potentiometers and twist angles between the rotary axes of the potentiometers will include: (1) no interference with the natural modes of intervertebral motion, (2) adjustability to detect and measure all components of motion, (3) negligible weight in comparison to the weight of the spine specimen and (4) ease of fabrication and installation on the specimen.

Because of the small size of the human vertebrae, the linkage transducer needs to be small. This imposes a constraint on the design of rotary potentiometers that are expected to measure the relative angular displacements of the links of the mechanism. Such small angular displacement potentiometers are fabricated by a commercial producer according to a given set of specifications listed in Table 4. Because of the small net displacements of the individual vertebrae contributing to the total motion of spine, the mechanical rotary input to the potentiometers is small. A mechanical amplifier is therefore needed to amplify this relative motion signal. This may be achieved by a small planetary friction roller train integrated with the rotary potentiometer as shown in Figure 24. The planet arm which carries the planet rollers is attached to one of the links (say L1). The extended outer casing of the rotary potentiometer which also carries the winding core is fixed to the second link L2, and acts as the ring roller. The sun roller carries the wiper of the rotary potentiometer.

With this arrangement the relative rotary motion input to the potentiometer is amplified, thus increasing the resolution of the individual potentiometer and of the entire linkage transducer. One possible set of specifications of such an epicyclic friction roller train are listed in Table 4.

Installation of such a linkage transducer is performed using the following stepwise procedure:

1. Calibrate the linkage transducer for an estimated range of data collection,
2. Attach one end of the linkage transducer rigidly to one vertebra through the use of Steinmann pins threaded into the cancellous bone of the vertebra. Attach the other end of the linkage transducer to the other vertebra using the same procedure. This method of attachment will prevent any relative motion between the vertebra and the link. When properly mounted the linkage transducer will spiral around the two vertebrae thus giving the needed length for the linkage transducer.
3. Establish a reference system for each vertebra and in the reference system locate all the links of the mechanisms at every instant mathematically using geometric parameters of the linkage transducer.
4. Establish the position and orientation of the reference system in each vertebra with respect to the geometric shape of

TABLE 4

SPECIFICATIONS FOR THE ROTARY POTENTIOMETERS AND THE EPICYCLIC FRICTION ROLLER TRAIN

Specifications for a Potentiometer

Outside Diameter	3/8 in.
Length	9/32 in.
Shaft Diameter	1/8 in.
Length	7/8 in.
Total Mechanical Travel	360° continuous
Theoretical Electrical Travel	$350^{\circ} \pm 5^{\circ}$
Total Resistance	5000 ohms $\pm$ 10%
Independent Linearity	$\pm$ 1%
Theoretical Resolution	0.2%
Running Torque	1.0 oz-in. (nominal)

Specifications for an Epicyclic Friction Roller Train

Diameter of the Sun Roller	1/8 in.
Diameter of the Planet Roller	3/32 in.
Length of Planet Arm	7/64 in.
Inside Diameter of Ring Roller	5/16 in.
Outside Diameter of Ring Roller	3/8 in.

the vertebra.

The kinematic principles of the linkage transducer as discussed in the previous sections reveal that there is more than one way in which the links of the transducer can be put together. This gives the investigator the required flexibility in selecting the optimum design and installation procedure to evolve the most efficient and accurate means to measure the three dimensional intervertebral relative motion.

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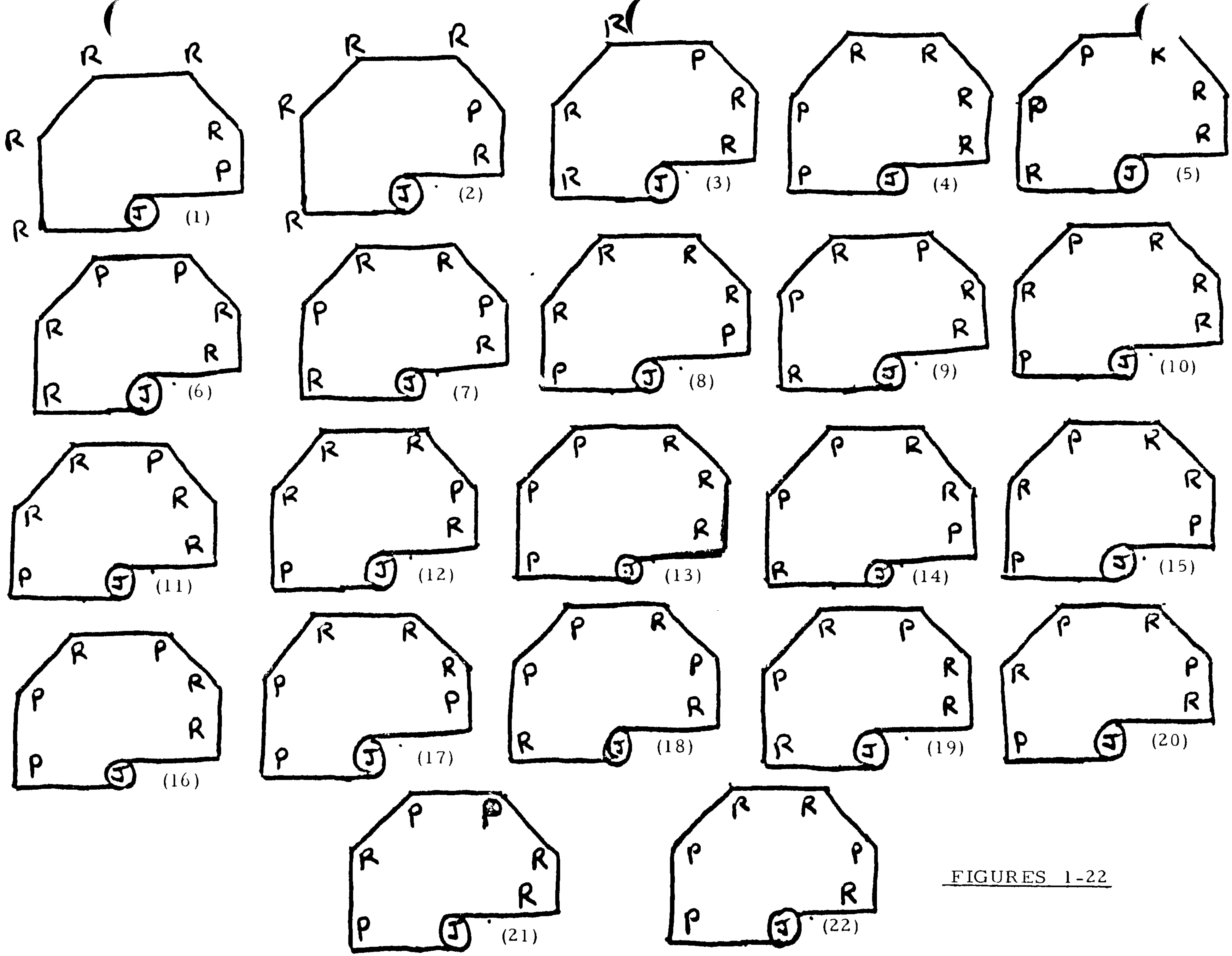
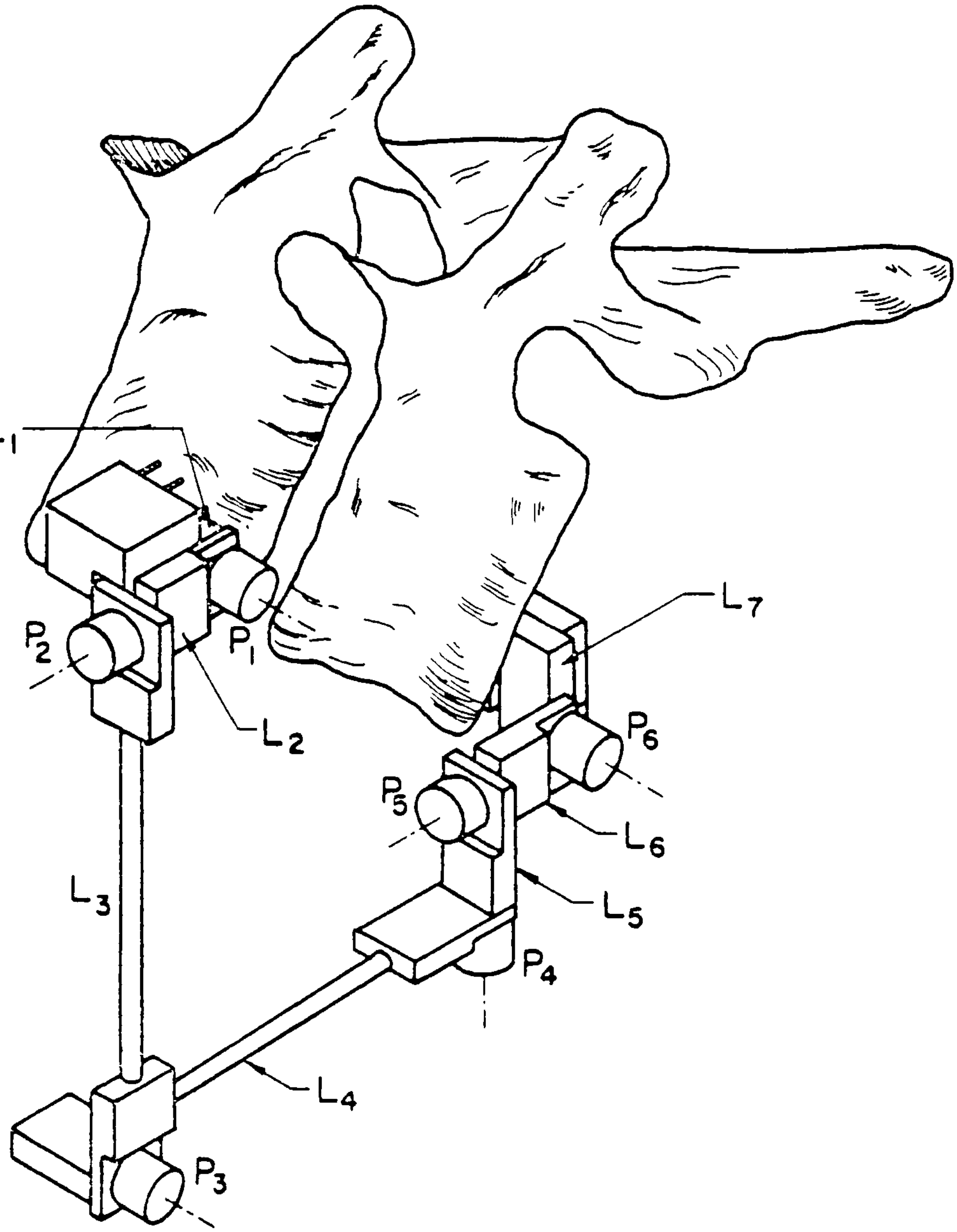
TYPES OF LINKAGE TRANSDUCERS



FIGURES 1-22



L_1 TO L_7 : LINKS OF THE LINKAGE TRANSDUCER

P_1 TO P_6 : ROTARY POTENTIOMETERS

FIGURE 23. SCHEMATIC ARRANGEMENT OF A LINKAGE TRANSDUCER BETWEEN A PAIR OF VERTEBRAE.

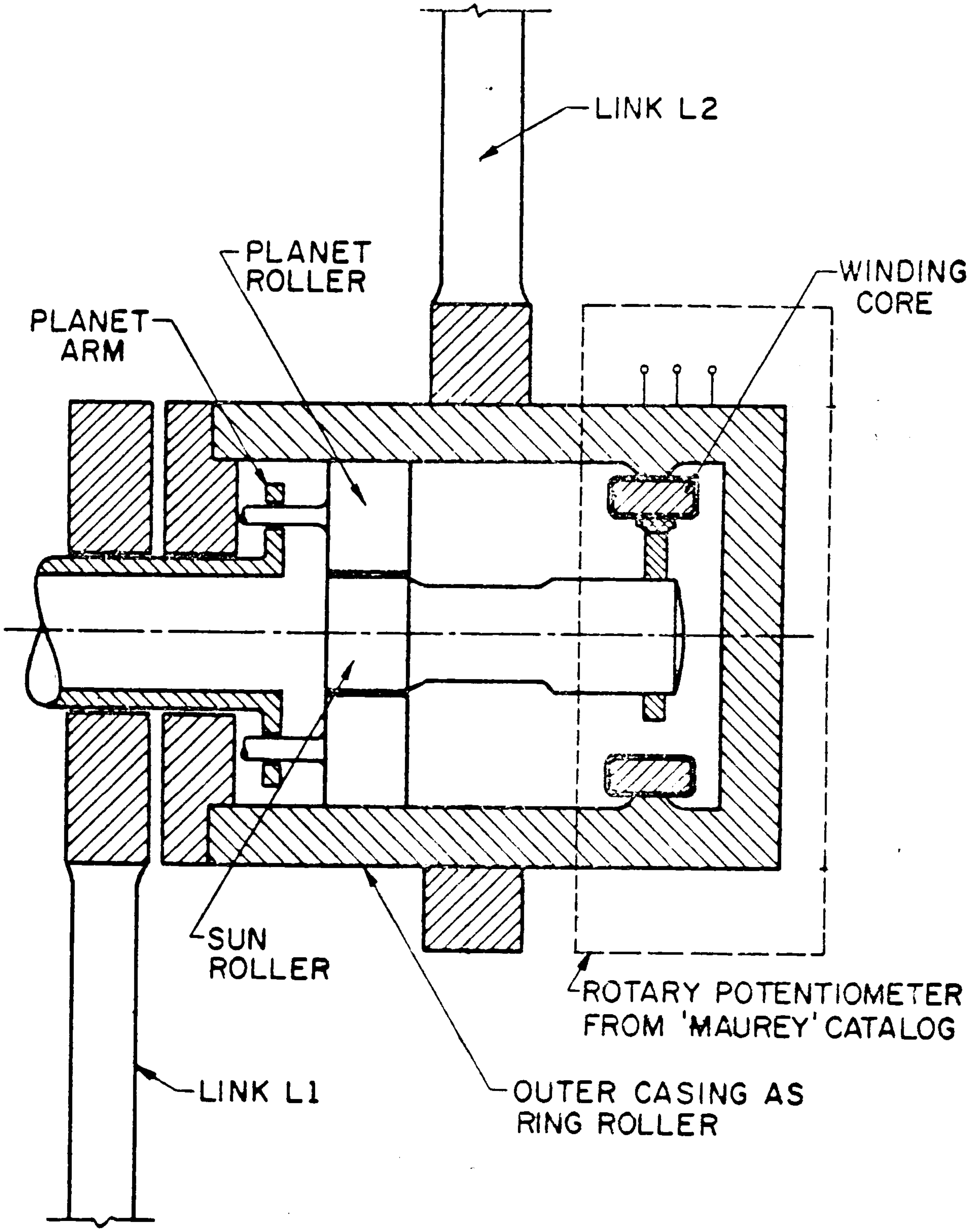


FIGURE 24. A SCHEMATIC DIAGRAM OF AN INTEGRATED ROTARY POTENTIOMETER.